REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
17-12-2015	Final Report	1-Aug-2011 - 31-Jul-2015

4. TITLE AND SUBTITLE
Final Report: Nanoscale Measurements of Magnetism & Spin Coherence in Semiconductors

5a. CONTRACT NUMBER
W911NF-11-1-0262

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS
Sangjun Jeon, Yonglong Xie

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
Princeton University
PO Box 0036
87 Prospect Avenue - 2nd floor
Princeton, NJ 08544 -2020

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
58486-MS.7

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
Under this grant, we have developed state of the art scanning tunneling microscope (STM) instrumentation that is able to characterize spin information on the atomic scale. In particular, we have developed the capability to perform spin polarized STM reliably using a vector magnet STM system and have developed protocols for creating spin polarized STM tips for reliable measurements. We have used these tools to study ferromangnetism in atomic chains of Fe and demonstrated that spin-orbit coupling at the surface of Pb can be detected with spin-polarized STM

15. SUBJECT TERMS
spin polarized measurements, single spins, single spin manipulation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Ali Yazdani
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					609-258-4390

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: Nanoscale Measurements of Magnetism & Spin Coherence in Semiconductors

ABSTRACT

Under this grant, we have developed state of the art scanning tunneling microscope (STM) instrumentation that is able to characterize spin information on the atomic scale. In particular, we have developed the capability to perform spin polarized STM reliably using a vector magnet STM system and have developed protocols for creating spin polarized STM tips for reliable measurements. We have used these tools to study ferromangnetism in atomic chains of Fe and demonstrated that spin-orbit coupling at the surface of Pb can be detected with spin-polarized STM measurements. In the last year, we have extended our spin polarized measurements to perform energy-resolved spin-resolved STM measurements on spin-polarized localized states of a superconductor created by magnetic defects. These energy-resolved studies are distinct from typical spin-selective measurements performed previously using the STM in any system. In addition, during the last year, we have developed a new platform for study of single spins in Si using specially fabricated Si-on-insultor devices. These SOI devices will provide the samples required for study of spin coherence at a single spin level in a semiconductor, with long coherence time.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/13/2015	3.00	S. Nadj-Perge, I. K. Drozdov, J. Li, H. Chen, S. Jeon, J. Seo, A. H. MacDonald, B. A. Bernevig, A. Yazdani. Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor, Science, (10 2014): 602. doi: 10.1126/science.1259327
01/13/2015	5.00	Jelena Klinovaja, Peter Stano, Ali Yazdani, Daniel Loss. Topological Superconductivity and Majorana Fermions in RKKY Systems, Physical Review Letters, (11 2013): 186805. doi: 10.1103/PhysRevLett.111.186805
01/13/2015	4.00	Jian Li, Hua Chen, Ilya K. Drozdov, A. Yazdani, B. Andrei Bernevig, A. H. MacDonald. Topological superconductivity induced by ferromagnetic metal chains, Physical Review B, (12 2014): 235433. doi: 10.1103/PhysRevB.90.235433
08/28/2013	2.00	I. K. Drozdov, B. A. Bernevig, Ali Yazdani, S. Nadj-Perge. Proposal for realizing Majorana fermions in chains of magnetic atoms on a superconductor, Physical Review B, (07 2013): 0. doi: 10.1103/PhysRevB.88.020407

TOTAL: 4

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. KITP Conference on Spin-Orbit Systems, Santa Barbara, August 2015.
2. Spintech, Basel, Switzerland, August 2015.
3. Gordon Conference on Topological States, Hong Kong University of Science and Technology, June 2015.
4. APS March Meeting 2015, San Antonio, TX, March 2015.
5. Annual Meeting of American Association for Advancement of Science, Symposium on From Novel Imaging to Novel Physics, San Jose, CA, February 2015.

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
12/17/2015	6.00	Ali Yazdani. Visualizing Majorana fermions in a chain of magnetic atoms on a superconductor, Nobel Symposium 156, New forms of matter: topological insulators and superconductors. , . : ,

TOTAL: 1

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/28/2013	1.00	S. Misra, B. B, Zhou, I. Drosdov, J. Seo, L. Urban, A. Gyneis, S. C. J. Kingsley, H. Jones,, A. Yazdani. Design and performance of an ultra-high vacuum scanning tunneling microscope operating at dilution refrigerator temperatures and high magnetic♀fields, Review of Scientific Instruments (08 2013)
TOTAL:		**1**

Number of Manuscripts:

Books

Received	Book
TOTAL:	

Received	Book Chapter
TOTAL:	

Patents Submitted

Patents Awarded

Awards

Elected Fellow of American Academy of Arts and Sciences
Einstein Lecturer, Weismann Institute, Israel

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yonlong Xie	0.30	
FTE Equivalent:	**0.30**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Sangjun Joen	0.20
FTE Equivalent:	**0.20**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Ali Yazdani	0.20	No
FTE Equivalent:	**0.20**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

During this grant, we developed key capabilities to probe single spins in solid state systems using the STM. We built instrument capable of performing spin polarized measurements and at ultra low temperature and in the presence of a vector magnetic fields. The ability to use a vector magnet combined with our efforts in fabricating spin polarized tips reliable led to highly reproducible spin polarized measurements. We used these to study chains of magnetic atoms on a superconductors, experiments in which we demonstrated our ability to make measurements of magnetism down to the atomic level and also for the first time probe spin orbit coupling. This system led to first direct visualization of a Majorana fermion in a condensed matter setting.
Our spin polarized tools where also used to probe single spins in Si, to probe donor and acceptor spins. However, it was found that such Si samples where not appropriate for single spin measurements. As they are too conducting or dominated by large interaction with other dopants. So during the last year, we developed new type of samples, in which we used a silicon-on-insulator (SOI) devices that were specifically designed to have conducting and non-conducting regions as well as back gates. These are unique samples that are now fabricated and are being examined in our lab. The fabrication of these samples required us collaborating with colleagues in CNRS in France who are Si device experts. We are currently are developing the ability to clean the surface of these devices and are aiming to use them to perform first single donor experiments with the STM in a getable structure. This will overcome the previous shortcoming in terms of samples used to probe single spins in semiconductors.
In the last year, we have also developed the capability to perform energy resolved spin-selective measurements, such as that we can evaluate the degree of a sharp energy levels near the chemical potential with the STM. This required use to find ways in which the spin polarization of the tips used can be tested near the Fermi level. We have applied this techniques to demonstrate that we can detected localized spin-polarized states in a superconductor near magnetic atoms. We are in the process of finishing these experiments and writing up the results. Overall, the program was successful in develop the tools required for high resolution experiments on single spin, and to manipulating them, but our short coming were in designing the appropriate sample, which was only developed recently after considerable effort.

Technology Transfer

None